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An Octave Bandwidth, High PAE, Linear, Class J GaN High Power Amplifier

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14. ABSTRACT

In this paper, the design and measured performance of a wideband (1.2-2.5 GHz), high efficiency, high linearity, Gallium Nitride (GaN), Class J, 200-W power amplifier (PA) is reported. The Class J PA output stages exhibit 45-62% power-added efficiency (PAE) and a near-maximum power match over > 2:1 bandwidth, and impressive 802.11g WLAN linearity. This linear PA has 65 to 70-dB small-signal gain over this bandwidth.

15. SUBJECT TERMS

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Abstract: *In this paper, the design and measured performance of a wideband (1.2-2.5 GHz), high efficiency, high linearity, Gallium Nitride (GaN), Class J, 200-W power amplifier (PA) is reported. The Class J PA output stages exhibit 45-62% power-added efficiency (PAE) and a near-maximum power match over > 2:1 bandwidth, and impressive 802.11g WLAN linearity. This linear PA has 65 to 70-dB small-signal gain over this bandwidth.*

Keywords: amplifier; power amplifier; high power amplifier; Class J; GaN; wideband; high efficiency; high PAE; linear amplifier; 2:1 bandwidth; octave band.

Introduction

The purpose of this work was to design, build and test a high power amplifier using a Class J design technique. The Class J technique was chosen because it has been recently demonstrated that an amplifier with near-optimum power and efficiency output match could be obtained over a wider bandwidth than possible using conventional techniques [1]. The frequency range of the amplifier was chosen to cover the complete range of US military L- and S-band telemetry frequencies from 1400-2450 MHz with a single amplifier. In theory, a Class J amplifier can support up to a 2:1 bandwidth; so covering the whole bandwidth with a single amplifier seemed quite an achievable goal.

The customer for this work was the Department of Defense's Spectral Efficient Technology (SET) division of Test and Evaluation/Science and Technology (T&E/S&T) and the integrated Network Enhanced Telemetry (iNET) group. SET required linear amplification of an 802.11g WLAN (or similar) complex waveform with an average output power of 10-W and close to 100-W peak output power. Previous work [2] had demonstrated a saturated output power of 30-W. The new specs therefore required larger transistors and a power combining technique to achieve 100-W saturated output power. Larger transistors require lower optimum real impedances for power and efficiency match, which is more difficult to achieve over a wide bandwidth. Previous work had utilized gallium arsenide (GaAs) pHEMT transistors with an operating voltage of about 10 V. Using the same technology to reach higher power levels, the real impedance required for optimum power and efficiency match becomes unrealistically small. GaN transistors provide higher load impedances for high output power, simplifying matching, and can safely operate at 28 V. This provides higher overall efficiency since the DC-DC converter can operate more efficiently using the required 28 V aircraft bus available for power.

The small-signal gain requirement for the PA was > 60-dB (65 to 70-dB achieved). This enables a < 0 dBm (1 mW) RF source to drive the PA, and also poses a stability risk for a single module in that there is a potential for oscillations due to signal feedback. The PA provides 200-W saturated power with high efficiency over 2:1 bandwidth, with 65-dB small-signal gain, and provides stable operation into high SWR loads. No published amplifiers have demonstrated these capabilities in the past.

Class J Design

In previous work, a 45-W GaN transistor was used as a basic building block in the amplifier. Four 45-W transistors were combined in parallel to achieve the required > 100-W power after combining losses. Each of these transistors operated as a stand-alone 50-ohm amplifier.

The Class J topology was chosen to obtain a high power-added efficiency (PAE) across the whole band. Using this type of amplifier, other papers had reported a drain efficiency of > 60% -70% [1,3] The goal for this design was to obtain a > 60% drain efficiency, thus matching the state-of-the-art, but providing it over a larger bandwidth than reported in the literature (50% and 43% bandwidth for [1] and [3], respectively). SET also required a much higher 10-W linear output power than earlier reported in the literature.

The key advantage of Class J amplifiers for broadband applications is the much larger load impedance design space available for optimal efficiency and power matching. This not only simplifies the output matching network but also allows the lower optimal impedance match of a larger transistor to be realizable over a wide band. The Class J design includes matching the impedances of the first and the second harmonics of the device at each frequency. Although this complicates the design process, the Class J mode allows the first harmonic load to look reactive as long as the second harmonic load is reactive as well.

As shown in [1], the ideal Class J optimum impedances for the first and second harmonics are, respectively:

$$Z_{f_0} = R_L + j \cdot R_L \qquad (1)$$

$$Z_{2f_0} = 0 - j \cdot 3\pi \cdot R_L / 8 \qquad (2)$$

Using equations (1) and (2), the real and reactive parts of the first and second harmonics can be set for Class J operation at an optimal output power and efficiency load. Class J allows for an optimal load target that does not require the first harmonic to lie on the real axis of the Smith chart, as required for Class A, B, and AB amplifiers [4]. Because Class J requires the first and second harmonic to be optimally load matched, operation beyond a 2:1 bandwidth is very limited since the first and second harmonic load targets have very different optimal impedances. Operating outside of a 2:1 bandwidth requires a compromised output load match at the band edges, but relatively good performance can be achieved up to a 2.2:1 bandwidth, as demonstrated in this design.

Using the AWR Microwave Office software program, a Class J amplifier was designed and simulated for continuous Class J operation. The design was fabricated onto RF boards and tested. The design met gain, return loss, power, and efficiency with first-pass success. Figure 1 shows the measured versus the modeled small-signal gain and return loss response of the Class J amplifier using a 45-W CREE GaN HEMT. The amplifier has a gain of 13 to 14 dB in the US military L- and S-band telemetry frequency range. In/out return loss is > 11 dB over most of this band. There is excellent correlation between the modeled and the measured data, showing both the accuracy of the transistor model in a Class J mode of operation and the AWR passive circuit simulation accuracy.

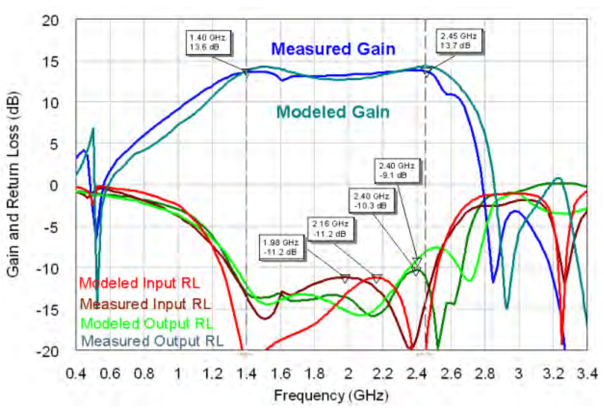

Figure 1. 45-W GaN Class-J Amplifier Measured vs. Modeled Small-Signal Gain and Return Loss

Figure 2 shows the measured power, large-signal gain, and PAE of the Class J 45-W GaN output amplifier stage. This design achieved 45 to 59-W saturated output power, near constant 10-dB large-signal gain, and 45 to 62% PAE from 1.1 to 2.45 GHz. For a 45-W transistor, this reveals a Class J amplifier load that is at or near the optimal power and efficiency load targets over a 2.2:1 or 76% bandwidth. Power-added efficiency (PAE) was slightly lower than expected but was > 50% from 1.35 to 2.35 GHz, or 48% bandwidth. Drain efficiency is shown in Figure 3 and is over 55% for this bandwidth, just slightly lower than that reported in [1].

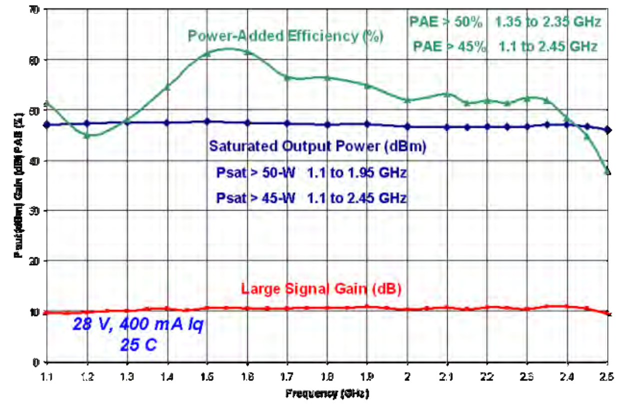

Figure 2. 45-W GaN Class-J Amplifier Measured Power-Added Efficiency, Output Power, & Large-Signal Gain

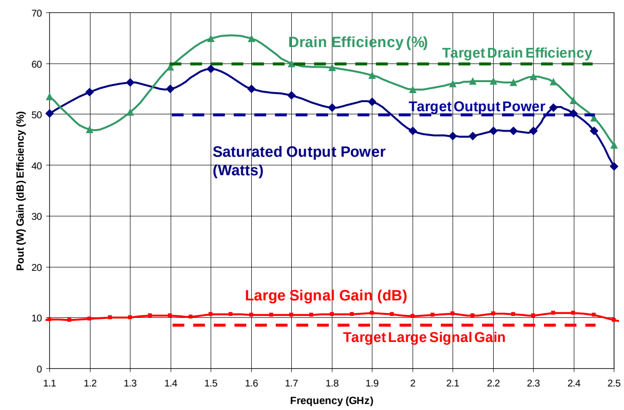

Figure 3. 45-W GaN Class-J Amplifier Measured Drain Efficiency, Output Power, & Large-Signal Gain

Figure 3 also shows the efficiency, power and gain targets, showing average performance over frequency to be close to target.

Figure 4 shows the measured peak and average power results versus frequency of the 45-W GaN output amplifier stage tested with an 802.11g WLAN digitally modulated signal. The measurements show the maximum output power of the signal modulated with QPSK (18 Mbps data rate) and an EVM of -14 dB or better; at 16-QAM (36 Mbps) and an EVM of -20 dB or better; and at 64-QAM (54 Mbps) and an EVM of -24-dB or better, at frequency points across the operating band. All of these data points were taken at the optimal bias condition which was found to be 28 V with a quiescent (small-signal) bias current of 400 mA for 16-QAM and 64-QAM, and 600 mA for QPSK. The amplifier performance using QPSK at 400 mA is nearly identical to the 600 mA bias performance.

The dotted line just below 35-dBm represents the minimum required average output power of the individual 45-W Class-J amplifier sub-circuits to achieve at least 10-W average power with four subcircuits quad combined. Both the QPSK and the 16-QAM cases meet this requirement. 64-QAM signals are actually linear at -20 dB EVM (instead of -24 dB as measured) according to certain standards and therefore do meet the required minimum level to achieve 10-W combined average power. This was not reflected in the plots however. Linearity is very constant over frequency, attesting to the output power flatness of the Class-J amplifier. This proved to be a valuable performance characteristic at the system level.

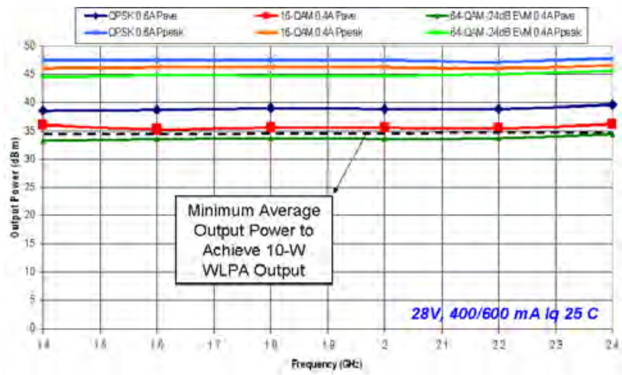

Figure 4. 45-W GaN Class-J Amplifier Measured WLAN Linearity vs. Frequency

WLPA Performance

With the Class J amplifier design complete, the Wideband Linear Power Amplifier (WLPA) module assembly began. The WLPA consists of four 45-W Class J amplifiers in parallel, driven by a fifth 45-W Class J amp along with lower-efficiency wideband amplifier stages. Through careful effort, the WLPA module was assembled and tested in the Cobham Richardson facility. Figure 5 shows the measured linear gain response of the complete WLPA module. The amplifier has a gain of 65-70 dB in the frequency range of 1.2-2.5 GHz, or 70% bandwidth. This gain level exceeded the SET requirement by 5 to 10-dB.

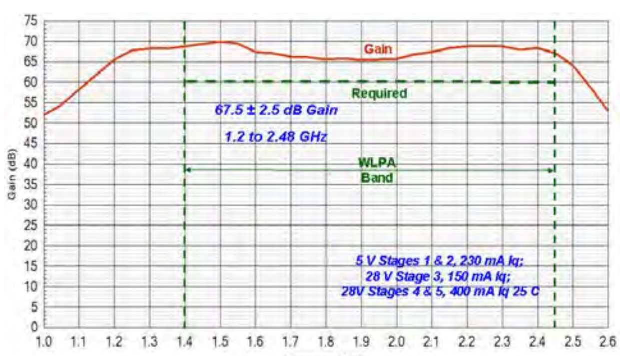

Figure 5. WLPA Small-Signal Gain vs. Frequency

Figure 6 shows the measured average output power for the entire WLPA module for an 802.11a WLAN complex waveform with 9 to 10-dB peak-to-average ratio. The red curve shows the QPSK average output power between 10 and 40-W from 1.2 to 2.5 GHz. Higher data rate architectures of 16- and 64-QAM were also measured and are displayed in Figure 6. With a -20-dB EVM requirement for the 64-QAM WLAN signal, the PA demonstrated > 10-W average output power in all four iNET operating bands, indicated in Figure 6. This met the most important customer requirement of the WLPA.

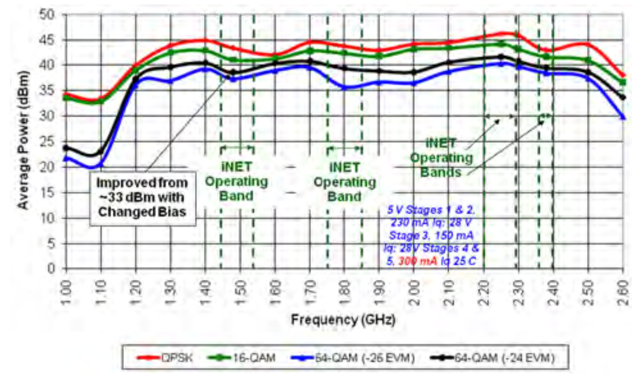

Figure 6. WLPA Measured 802.11a WLAN Average Power vs. Frequency

Figure 7 shows the measured peak output power of the WLPA. The red curve shows the QPSK peak output power to be between 110 and 210 W from 1.2 to 2.5 GHz. This data shows the additional headroom available from the amplifiers for brief periods of power spikes characteristic of high peak-to-average-ratio of complex waveforms.

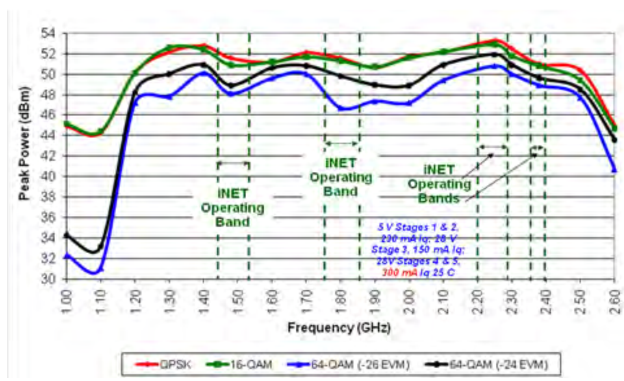

Figure 7. WLPA Measured 802.11a WLAN Peak Power vs. Frequency

Figure 8 shows the measured PAE of the WLPA for 802.11g WLAN signals. The red curve shows the QPSK PAE to be 9- 23% from 1.2 to 2.5 GHz and between 15-23% from 1.3 to 2.5 GHz or over 63% bandwidth. These efficiencies are lower than those shown earlier because of the back-off required for linear transmission of the 802.11g signals. The efficiency also lower because of the WLPA combining losses and additional DC power required for the COTS driver stages.

The WLPA meets SET requirements and allows the use of a single amplifier where four parallel systems of amplifiers would have been required using conventional power amplifiers. Class J may prove to be a very useful technology in multiband transmitter applications, allowing total system size, weight, and power to be significantly reduced. Figure 9 shows a photo of the completed WLPA module.

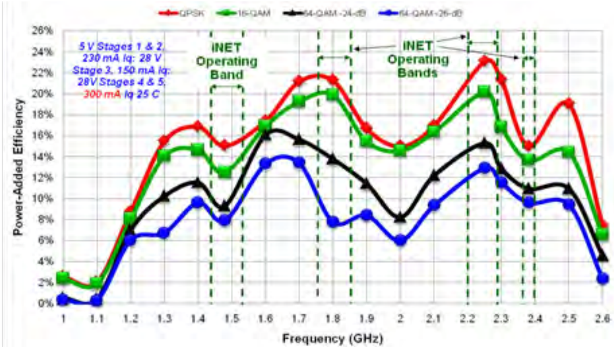

Figure 8. WLPA Measured 802.11a WLAN Power-Added Efficiency vs. Frequency

Figure 9. Photo of Completed WLPA Module [5]

Conclusions

The performance results for a state-of-the-art linear power amplifier were presented. These results show the wide frequency band capability of a Class J amplifier while maintaining near-optimum output power and efficiency loads over a 2.2:1 bandwidth. Linearity results show that the Class J configuration does not degrade the linearity of the transistor, providing linear operation of 802.11g WLAN complex waveforms with up to 64-QAM modulation. Operating at peak power levels up to 210-W, the WLPA represents a significant advancement for wideband, high efficiency, high power, linear amplifiers.

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